

Green Hydrogen in Agriculture: Promoting Climate-Smart and Energy-Independent Farming Systems

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ABSTRACT

Agriculture is a resource- and energy intensive sector and contributes substantially to global greenhouse gas emissions. Adopting clean and renewable energy technologies that minimize impact on the environment while preserving energy security is necessary for transitioning toward sustainable agriculture systems. A prospective zero-carbon energy source for agriculture is green hydrogen, which is produced by electrolyzing water using renewable electricity. It may find use in climate-smart agricultural systems, hydrogen-powered farm equipment, renewable energy storage, and sustainable fertilizer manufacturing. With a focus on potential for sustainable agricultural development, this article examines the idea of "green hydrogen," its production processes, and its possible uses in agriculture.

Keywords: Green hydrogen, sustainable agriculture, renewable energy, green ammonia, climate-smart farming, decarbonization

1. Introduction

Agriculture plays a crucial role in global food security and rural livelihoods, yet it contributes significantly to climate change, which is associated with serious environmental impact. The global agri-food system is responsible for around one-third of all anthropogenic greenhouse gas emissions due to land-use changes, farm operations, and supply chain activities (Crippa et al., 2021; FAO, 2022). The growing energy needs in agriculture, especially for irrigation, mechanization, and fertilizer production, have increased reliance on fossil fuels and, thereby, carbon emissions.

To address these environmental challenges, renewable energy technologies are being promoted globally to meet climate mitigation targets and support sustainable agricultural production. Among them, green hydrogen has drawn considerable attention as a clean energy carrier that can lower reliance on fossil fuels and promote sustainable farming practices (IEA, 2019; Maganza et al., 2023).

2. Concept of Green Hydrogen

A fuel with a high energy density, hydrogen can be produced from a variety of energy sources. Green hydrogen is produced by electrolyzing water using renewable energy

sources like solar and wind power to split it into hydrogen and oxygen (Panigrahy et al., 2022; Maganza et al., 2023).

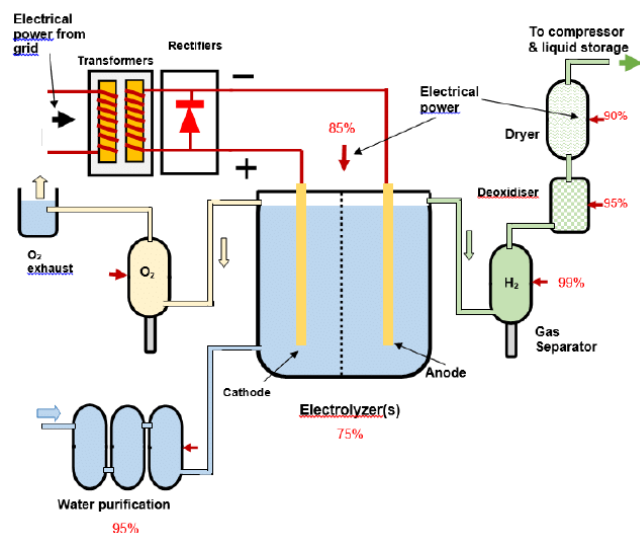
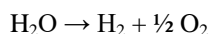


Figure 1. Schematic representation of hydrogen production through electrolysis (Sangster, 2015).

The electrolysis reaction is



This method is environmentally beneficial since it generates hydrogen fuel without emitting carbon dioxide (IRENA, 2020).

Common classifications for hydrogen include:

- **Grey hydrogen** is produced from fossil sources with high emissions.
- **Blue hydrogen** is carbon-captured hydrogen derived from fossil fuels.
- **Green hydrogen** is carbon-free and based on renewable energy (IEA, 2019).

Fossil fuels currently account for approximately 95% of the world's hydrogen production, underscoring the need for greener production methods (IEA, 2022).



Figure 2: Fukushima Hydrogen Energy Research Field (FH2R), one of the world's largest hydrogen production facilities using renewable energy. (Source: Government of Japan. Available at:

<https://www.japan.go.jp/kizuna/2021/03/hydrogen-production-facility>)

3. Necessity for Green Hydrogen in Agriculture

Agriculture relies heavily on fossil fuels for nitrogen fertilizer production, farm machinery, irrigation systems, and post-harvest processing. Conventional fertilizer ammonia production uses natural gas-derived hydrogen, which dramatically raises greenhouse gas emissions (IEA, 2019).

The application of green hydrogen technologies can boost sustainability within agricultural production systems (van Renssen, 2020). Additionally, incorporating renewable energy sources into agriculture lowers reliance on imported fossil fuels and increases energy security (Gorjian et al., 2022).



Figure 3: Conceptual presentation of green hydrogen production from wind and solar energy (Source: Carnegie Institution for Science, Available at:

<https://carnegiescience.edu/news/green-hydrogen-production-curtailed-wind-and-solar-power>)

4. Production Pathways of Green Hydrogen

4.1 Water Electrolysis

The primary process for generating green hydrogen is water electrolysis. Alkaline water electrolysis, solid oxide electrolysis, and proton exchange membrane electrolysis are important electrolysis technologies (Kumar and Himabindu, 2019). The performance of electrolyzers and the availability of renewable electricity determine the efficiency and cost-effectiveness of hydrogen production (Turner et al., 2008).

Hydrogen generated through electrolysis may be stored, compressed, or used through fuel-cell systems to produce heat and power without emitting greenhouse gases (IRENA, 2020).

4.2 Hydrogen Production from Agricultural Biomass

Thermochemical and biological processes, including gasification, pyrolysis, and microbial electrolysis, can also be used to manufacture hydrogen from organic residues, manure, wastewater, and agricultural waste (Kadier et al., 2016; Buffi et al., 2022). Through the conversion of agricultural waste into renewable energy resources, this method promotes circular agriculture. However, because of financial and technological constraints, biomass-based hydrogen production is still in its infancy (Buffi et al., 2022).

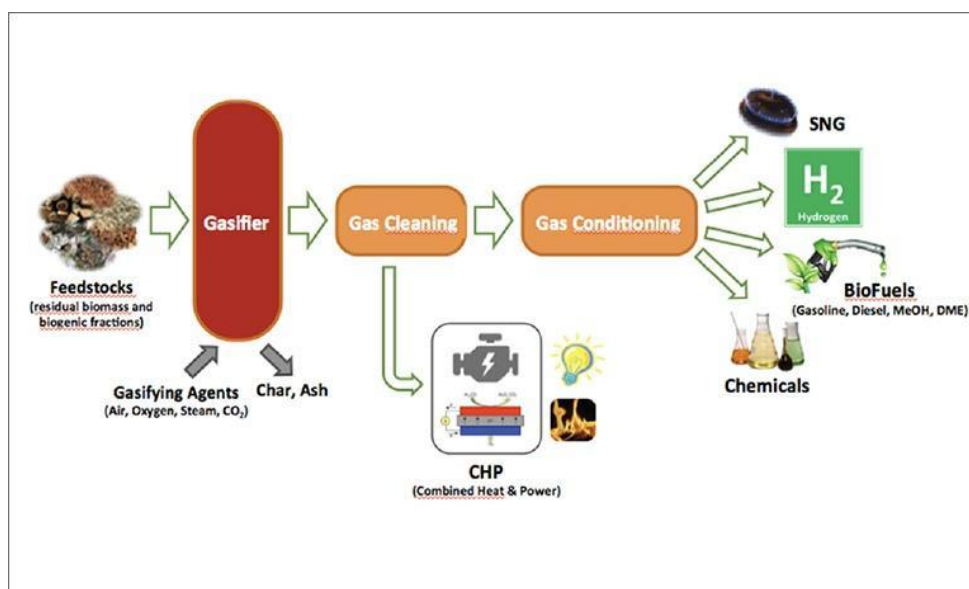


Figure 4. General process steps involved in biomass gasification and related producer gas generation (Barisano, Available at: [Green hydrogen through biomass gasification](#))

5. Applications of Green Hydrogen in Agriculture

5.1 Green Ammonia for Fertilizer Production

Hydrogen is a critical component in ammonia synthesis, used for nitrogen fertilizers. Green ammonia can be produced using green hydrogen, thereby lowering emissions associated with fertiliser production (IEA, 2019; van Renssen, 2020). Low-carbon agriculture and sustainable nutrient management can greatly benefit from this.

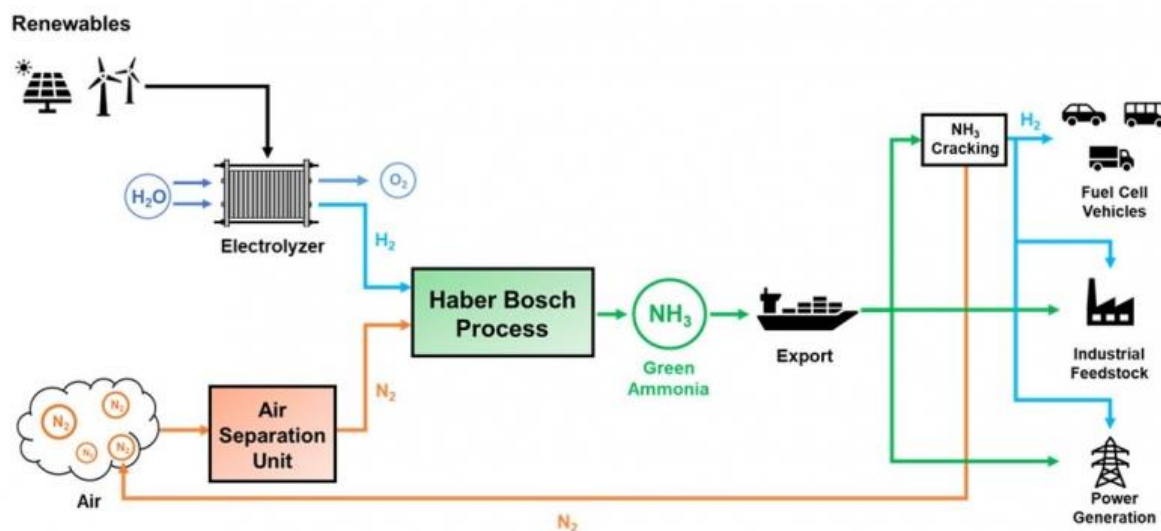


Figure 5: Alternative green pathways for ammonia production using hydrogen gas (Source: UNSW Photocatalysis Research Group, Available at: <https://www.pcrgr.unsw.edu.au/>)

5.2 Hydrogen-Powered Agricultural Machinery

Water vapour is the only byproduct of the chemical interactions between hydrogen and oxygen that produce power in hydrogen fuel cells. By powering tractors, irrigation pumps, and other farm equipment, these fuel cells can lessen environmental pollution and the need for diesel fuel (Maganza et al., 2023; van Renssen, 2020).



Figure 6: The world's first hydrogen-powered tractor (Source: H2 Dual Power Project, Available at: <https://h2dualpower.com/en>)



Figure 7: World's First Hydrogen Fuel Cell Autonomous Tractor developed by Kubota.

(Source: Equipment World. Available at: <https://www.equipmentworld.com/>)

5.3 Renewable Energy Storage and Rural Electrification

The intermittent nature of solar and wind energy can be effectively managed by using hydrogen as an energy storage medium. Excess renewable energy can be stored as hydrogen and used to supply power to agro-processing units, cold storage facilities, and power irrigation systems (IEA, 2022; Global Hydrogen Review 2022). These technologies

may reduce dependency on fossil fuels and enhance the energy supply in rural areas.

5.4 Greenhouse and Controlled Environment Agriculture

Hydroponic farms and greenhouses have implemented hydrogen-based energy systems to supply heating, electricity, and energy storage. Greenhouse operations can become environmentally sustainable and energy self-sufficient with integrated hydrogen and renewable energy systems (Global Hydrogen Review 2022).

6. Economic and Environmental Advantages

Green hydrogen has various benefits for sustainable agriculture:

- Decrease in emissions of greenhouse gases
- Enhanced energy security
- Effective use of renewable energy
- Encouragement of circular economy methods
- Decreased reliance on fossil fuels

These advantages support long-term agricultural sustainability and climate resilience (IRENA, 2020; Kakoulaki et al., 2021).

7. Challenges in Adoption

Despite its potential, green hydrogen has a number of obstacles to overcome, such as high production prices, inadequate infrastructure, storage issues, and technological hurdles (IEA, 2022). The widespread adoption of green hydrogen is constrained by the fact that its cost is significantly higher than that of hydrogen derived from fossil fuels (van Renssen, 2020). To address these limitations, technical breakthroughs, financial incentives, and supportive governmental frameworks are needed (Maganza et al., 2023).

8. Prospects for the Future

It is anticipated that green hydrogen would be crucial to the global shift to sustainable energy sources. Technological developments in agricultural waste utilization, renewable energy integration, and electrolysis could lower manufacturing costs and increase uptake. Future climate-smart farming may be supported, and resource efficiency increased, by integrating hydrogen production with agricultural systems (Global Hydrogen Review 2022).

9. India's National Green Hydrogen Mission and Agricultural Opportunities

India has made substantial advances toward promoting green hydrogen through the National Green Hydrogen Mission, launched in 2023 to establish India as a global centre for hydrogen production, utilization, and export. By 2030, the

mission aims to cut carbon emissions in energy-intensive industries, create at least 5 million metric tons of green hydrogen annually, and reduce the import of fossil fuels (Government of India, 2023; IEA, 2023).

The mission's primary objectives are to increase the capacity for renewable energy, build infrastructure for the production of hydrogen, encourage industry decarbonisation, and support research and innovation. India has a lot of potential for producing green hydrogen at a low cost thanks to its plentiful solar and wind resources, especially in rural and agricultural areas.

9.1 Implications for Agriculture

The National Green Hydrogen Mission presents several opportunities for the agricultural sector:

Sustainable fertilizer production

Conventional ammonia manufacturing is mostly dependent on imported natural gas, and India is one of the biggest consumers of nitrogen fertilizers. Long-term energy security can be enhanced, and carbon emissions can be decreased by using green hydrogen in fertilizer production (IEA, 2023).

Energy independence in rural areas

Decentralized electricity for irrigation, cold storage, and agro-processing facilities can be provided by green hydrogen systems combined with solar and wind energy, enhancing access to energy for rural communities.

Utilization of biomass and crop residue

By using thermochemical and biological conversion technologies, agricultural leftovers and organic waste can be used as feedstock for the production of hydrogen, promoting circular economy principles and lowering the need for burning residues.

Employment and the growth of agribusiness

In rural areas, the construction of renewable energy systems and hydrogen infrastructure can spur entrepreneurship and open up new job prospects.

9.2 Challenges and Policy Need

Despite strong policy support, several challenges still exist, including high investment costs, technological limitations, infrastructure requirements, and limited awareness among farmers. The successful execution of the mission requires capacity building, financial incentives, and integration with agricultural development programs (GoI, 2023).

Overall, the National Green Hydrogen Mission has an opportunity to revolutionize India's agricultural industry by encouraging the use of clean energy, cutting emissions, and bolstering sustainable farming practices.

9.3 Case Studies: The Fertilizer Industry in India Using Green Hydrogen

Case Study 1: Green Hydrogen for Ammonia Production by NTPC Renewable Energy Project

NTPC Ltd., a public sector power firm in India, has commenced testing green hydrogen generation using renewable energy. At its Vindhyachal Super Thermal Power Station in Madhya Pradesh, NTPC launched a green hydrogen plant into service in 2022. Solar-powered water electrolysis produces hydrogen, which is being investigated for use in fertiliser manufacturing and other industrial processes.

Additionally, NTPC has announced plans to build green hydrogen hubs that can provide hydrogen for the generation of green ammonia, a crucial component of nitrogen fertilizers. These initiatives show how ammonia synthesis can lower carbon emissions while incorporating renewable hydrogen into India's fertiliser production industry (NTPC Limited, 2022).

Case Study 2: IOCL-Fertilizer Sector Partnership for Green Ammonia

Using electrolysis based on renewable energy, Indian Oil Corporation (IOC) is constructing green hydrogen production facilities at multiple refineries. IOC is investigating the provision of green hydrogen in partnership with fertiliser firms to produce green ammonia, which can take the place of hydrogen derived from fossil fuels used in the Haber-Bosch process.

The fertiliser sector, which presently relies on hydrogen supplied from natural gas, may drastically cut emissions by using green ammonia. Green hydrogen usage in fertiliser plants could help India achieve its energy security objectives by lowering carbon intensity and reliance on fossil fuel imports (IEA, 2023).

Case Study 3: Odisha's Green Ammonia Project by ACME Group

One of the nation's first significant green hydrogen and green ammonia plants is being constructed in Odisha by Indian renewable energy producer ACME Group. The project's goal is to use solar and wind energy to generate green hydrogen, which will then be transformed into green ammonia for use in energy and fertiliser applications.

It is anticipated that the facility will generate large amounts of green ammonia, which can be exported or utilized domestically in the manufacturing of fertiliser. These initiatives show how India might develop into a worldwide centre for the manufacture of low-carbon ammonia, which could revolutionize the fertiliser sector and help achieve climate mitigation objectives (ACME Group, 2025).

Case Study 4: Green Hydrogen in Fertilizer Production – IFFCO

Indian Farmers Fertilizer Cooperative Limited (IFFCO) has partnered with ACME Cleantech to procure about 200,000 tonnes of green ammonia annually, produced using renewable hydrogen through water electrolysis at a facility in Gopalpur, Odisha. For the production of nitrogen fertilizer, IFFCO fertilizer production plants at Paradeep and Kandla will receive the green ammonia. This initiative supports India's National Green Hydrogen Mission and demonstrates the potential of renewable hydrogen to reduce emissions in the fertilizer industry (Business Standard, 2024).

These novel endeavours demonstrate the increasing drive to include green hydrogen in India's fertiliser industry. With a reduction in technology costs and an increase in policy support, green ammonia could be crucial to decarbonising fertiliser production and improving the sustainability of Indian agricultural systems.

10. Conclusion

Green hydrogen reflects a promising solution for transforming agriculture into a low-carbon and energy-efficient sector. Its potential to increase sustainability and lower environmental effects is demonstrated by its uses in controlled environment agriculture, fertilizer manufacture, agricultural mechanization, and renewable energy storage. Even if there are still technological and financial obstacles to overcome, further research, policy support, and innovation can enable widespread adoption of green hydrogen in agriculture, promoting sustainable food production and mitigating the effects of climate change.

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